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54 Title of the Invention

TUNING DEVICE FOR ROBOT CONTROL SYSTEM

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SPECIFICATION

1. TITLE OF THE INVENTION

TUNING DEVICE FOR ROBOT CONTROL SYSTEM

2. SCOPE OF PATENT CLAIM

(1) A tuning device for a robot control system in which a robot arm is caused to operate via a torque transmission mechanism while driving an actuator to a target value input to a control device body comprising:

an external sensor which detects an actual operation of the robot arm from an external side;

a compensation signal preparing unit which prepares a compensation signal for changing a target value so that the robot arm operates in accordance with the target value toward the target value input to the control device body while identifying a dynamic characteristic model concerned with an operation mechanism composed of the actuator, the torque transmission mechanism, and the robot arm using a detection signal of the sensor; and

a target value changing unit which changes the target value input to the control device body with the compensation signal prepared by the device.

(2) A tuning device for a robot control system in which a robot arm with relatively low rigidity is caused to operate while driving an actuator to a target value input to a control device body comprising:

an external sensor which detects overshoot amount at a direction changing point in a reciprocating motion of the robot arm from an external side;

a control constant which sets unit setting a control constant of a PID control system which forms the control

device body while identifying a dynamic characteristic model of the robot arm; and

a control constant fine adjusting unit which fine adjusts the control constant set by the control constant setting unit so that the overshoot amount falls within a prescribed value using a detection signal of the external sensor when the robot arm is caused to perform a reciprocating motion using a control constant set with the device.

(3) The tuning device for the robot control system according to claims (1) and (2), wherein the signal for identification, which signal is input to the actuator, is an M sequence signal to which DC bias is added.

(4) The tuning device for the robot control system according to claim (2), wherein the control constant setting unit sets the control constant of a speed control loop upon obtaining an open-loop frequency characteristic data and a closed loop frequency characteristic data of a speed loop using the frequency characteristic data, and subsequently, sets the control constant of a position loop upon obtaining an open-loop frequency characteristic data and a closed loop frequency characteristic data of the position loop while using the closed loop frequency characteristic data of the speed loop.

3. Detailed Description of the Invention

[Object of the Invention]

(Industrial Applicability)

The present invention relates to a tuning device for a robot control system in which a robot arm is caused to operate to a target value input while driving an actuator.

(Prior Art)

Generally, a joint structure of a robot is in a state shown in, for example, Fig. 26.

That is, there is connected a robot arm 4 via a torque transmission mechanism 3 such as a speed reducer or the like, to an actuator 2 such as motors with an actuator sensor 1 such as angle sensors, whereby a control signal u is output to the actuator 2 from the control device body 5 such as a PID control device or the like, such that a signal θ_m detected by the sensor 1 becomes equal to a target value θ_{mr}.

Here, conventionally, since a motor angle θ_m is equal to an arm angle θ_e in the case that rigidity of the torque transmission mechanism 3 is sufficiently high, a motor target value θ_{mt} is set as an arm target value θ_{er}.

On the other hand, although the completed robot should be set, for instance, a predetermined PID control constant in its PID control device by a so-called tuning work, conventionally, this work has been performed manually.

That is, the conventional tuning work is that appropriate control constant is set upon varying the PID control constant by trial and error while observing an actual operation of the robot.

(Problems to be solved by the Invention)

However, in the conventional manual tuning work, the PID constants of the PID control device are changed variously while observing the actual operation, therefore, there are problems that much labor and time are required in its work and tuning result is not necessarily good. Further, since this work requires skill along with much labor and time, it is not possible to tune according to secular change or depending on a load change of the arm fingers, timely as needed.

For that reason, conventionally, one so called as an adaptor is proposed in which dynamic characteristic is identified depending on a signal input to the actuator 2 and an output of the actuator 2, at the same time, the PID control constant is supplied to the control device body, however, there is inconvenience that the adaptor cannot come in practice in that vibrations take place on the robot arm 4 caused by backlash of the torque transmission mechanism 3 or low rigidity of the arm 4, as well as sufficient algorithm is not established.

By the way, as shown in Fig. 27, the actual operation θ_e of the arm 4 deviates considerably large and randomly to the target value θ_{mr} (θ_{er}) caused by the backlash of the torque transmission mechanism 3 or the low rigidity of the arm 4.

Accordingly, in a tuning device for a robot control system where a robot arm is caused to operate while driving an actuator to an input target value, it is an object of

the present invention to provide a tuning device for a robot control system capable of tuning such that the robot arm can be subjected to positioning control in low vibration with high accuracy.

[Constitution of the Invention]

(Means for solving the problem)

In order to solve the above mentioned problem, a tuning device for a robot control system of the present invention, as shown an outline in Fig. 1, in the tuning device for the robot control system where the robot arm 4 is caused to operate via a torque transmission mechanism 3 while driving an actuator 2 to a target value input to a control device body 5, the tuning device for the robot control system is characterized in that an external sensor 6 is provided, which detects an actual operation of the robot arm 4 from an external side; a compensation signal preparing unit 7 is provided, which prepares a compensation signal for changing a target value so that the robot arm 4 operates according to the target value in relation to the target value input to the control device body 5 while identifying a dynamic characteristic model concerned with an operation mechanism composed of the actuator 2, the torque transmission mechanism 3, and the robot arm 4 using a detection signal of the sensor 6; and a target value changing unit 8 is provided, which changes the target value input to the control device body 5 with the compensation signal prepared by the device 7.

Further, as shown in Fig. 2, in a tuning device for a robot control system in which a robot arm 4 with relatively low rigidity is caused to operate while driving actuator 2 to a target value input to a control device body 5, the tuning device for the robot control system is characterized in that an external sensor 6A is provided, which detects overshoot amount at a direction changing point in reciprocating motion of the robot arm 4 from an external side; a control constant setting unit 9 is provided, which sets a control constant of a PID control system for forming the control device body 5 while identifying a dynamic characteristic model of the robot arm 4; and a control constant fine adjusting unit 10 is provided, which fine adjusts the control constant set by the control constant setting unit 9 so that the overshoot amount falls within a prescribed value using a detection signal of the external sensor 6A when the robot arm 4 is caused to perform a reciprocating motion using a control constant set with the unit 9.

(Operation)

In tuning device TA of the robot control system of the present invention shown in Fig. 1, there is prepared a compensation signal for changing a target value so that the robot arm 4 operates just as the target value in relation to the target value input to the control device body 5 while identifying a dynamic characteristic model using an actual operation of the robot arm detected by the external sensor

6, and the target value is changed with a target value changing unit 8.

Further, the tuning device TB of the robot control system shown in Fig. 2, there is set a control constant of a PID control system for forming the control device body 5 while identifying the dynamic characteristic model using an operation detection signal of the actuator 2, and a reciprocating motion is provided to the robot arm 4 due to a set PID control constant, so that the PID control constant is fine adjusted based on overshoot amount detected by the external sensor 6A.

(Embodiment)

Hereinafter, there will be described an embodiment of the present invention.

Referring to Fig. 3, the tuning device TA1 as an embodiment of the tuning device TA shown in Fig. 1, in a control system composed of a PID control devise 5A, a motor 2A, a motor angle sensor 1A, a reducer 3A, and a robot arm 4, is constituted by attaching an external sensor 6 for detecting a point operation of the robot arm 4, a dynamic characteristic identification part 7A as a compensation signal preparing device 7, and a target value changing unit 8.

The external sensor 6 constituted with an acceleration sensor, a non-contact displacement sensor, three-dimension coordinate measuring instrument and the like, detects a current angle of a point position of the

robot arm 4 in real time by observing the point position of the robot arm 4 during a tuning work.

The dynamic characteristic identification part 7A, when performing the identification operation while sending a predetermined identifying signal with an identifying signal generator 9, obtains a frequency response in such a way that a motor angle θ_m detected by the motor angle sensor 1A and an arm angle θ_e detected by the external sensor 6 are input with the switch 11 on A side, before fitting it to ARMA model by the least-squares method shown in the following reference documents 1), 2). Next, there is prepared a compensation signal which serves a target value θ_{mr} toward a motor 2A as a target value θ_{er} toward the robot arm 4 input to a PID control device 5A, by obtaining a transfer function G(S) of continuous time using, for instance, "curved line adaptation" described in the following reference document 3) to the frequency response.

1) "Two-degree-of-freedom PID automatic tuning controller" by Shigemasa, Iino, Kanda, Toshiba Review, Vol. 42, Number 11, pp 822 to 826 (1987)

2) "Signal processing and System identification" by Nakamizo, Takayoshi, Colona Company (1988)

3) "Method for obtaining a transfer function by frequency response measuring value" by Yamashita, Suzuki, Fujii, Control Engineering, 14-11, pp 664 to 667 (1970)

That is, the transfer function G(S) of this case is

$$G(S)=\frac{\theta_m}{\theta_e}=\frac{M_e S^2+(D_e+D_G)S+K_G}{D_G S+K_G}\bullet N \qquad \cdots(1)$$

Here, since G(S) is obtained by

M_e is a moment of inertia of the arm;

D_e is viscous friction coefficient of the arm axis;

K_G is a spring constant of the reducer 3A;

D_G is twisting viscous friction coefficient of the reducer 3A;

N is reduction ratio (≥ 1); and

S is a Laplace operator.

By this means, a compensation value $\Delta\theta_r$ is prepared in order to serve a motor target value θ_{mr} as an arm target value θ_{me}, and which compensation value $\Delta\theta_r$ is set to the target value changing unit 8, thus, the robot arm 4 is controlled in low vibration and high positioning by the changed target value.

Further, in the robot generally, since the moment of inertia M_e of the arm in equation (1) changes according to an arm attitude or size of object to be grasped during operation, the robot is caused to have function to update a coefficient of S^2 of the target value changing unit 8 in real time. For instance, in the case of a two-joint robot in which one more arm is coupled to the robot arm 4 shown in Fig. 3, when letting an arm angle of the second joint be θ_{e2}, a motor angle be θ_{m2}, the moment of inertia M_{e2} around the first joint, because of $\sin\theta_{e2} \approx \sin\theta_{m2}$, is expressed by the following equation.

$$M_{e2} = M_e - M\sin\theta_{e2}$$
$$\approx M_e - M\sin\theta_{m2} \quad \ldots (2)$$

Here, M_e is the moment of inertia by arranging the first and the second joints; and

M is the moment of inertia around the second joint.

Thus, when replacing the moment of inertia M_{e2} obtained with the equation (2) into the moment of inertia M_e of the arm of the equation (1), it becomes possible to perform target value change corresponding to change of the arm attitude in real time.

On the other hand, in order to perform the target value change corresponding to size of the object to be grasped, with a timing to grasp the object to be grasped, with ΔM_e as a fluctuation part measured beforehand, while setting M_e as follows:

$$M_e \leftarrow (M_e + \Delta M_e) \quad \cdots \quad (3)$$

The moment of inertia M_e of the arm may be updated.

Furthermore, even though there is changed the dynamic characteristics such as secular change of the robot arm 4, the viscous friction coefficient D_e of the arm axis, the spring constant K_G of the reducer 3A, the twisting viscous friction coefficient DG of the reducer 3A and the like, the dynamic characteristic model identification part 7A responds to identify it, thus it is possible to perform control preferably if updating an identification model used in the target value changing unit 8.

Fig. 4 is a graph showing time response according

to this embodiment as apparent when comparing with conventional example shown in Fig. 27, the arm angle θ_e adequately follows a target arm angle θ_{er}.

As described above, according to the present embodiment, the target value changing unit 8 changes the target motor angle θ_e into the target arm angle θ_m and serves its value as the target value of the control system based on the identification model obtained with the dynamic characteristic model identification part 7A, thereby vibration of the arm point is suppressed. Therefore, it is possible to achieve reduction of positioning time and improvement of positioning accuracy of the robot arm 4.

Next, when referring to Fig. 5 as one embodiment of the tuning device TB of Fig. 2, in the tuning device TB1 of the present example, a motor 2A is connected to a software servo part 5B as the control device body 5 via a switch 11A, and the robot arm 4 is connected to the motor 2A via a joint member 3B.

The software servo part 5B, as shown in Fig. 6, is constituted of a position loop part 14 provided with a feed forward (FF) control part 12 and a proportional (P) control part 13, a speed loop part 17 provided with an integral (I) control part 15 and a P control part 16, and a numerical value differentiating part 18, in which target values of position and speed V_{mr}, θ_{mr} are input, and detected values θ_m, V_m are fed back to the target values of position and speed V_{mr}, θ_{mr}, so that output u is supplied to the motor

2A.

An identifying signal generating part 9A is arranged in parallel to the software servo part 5B. The switch 11A switches to input a signal to the motor 2A, which signal is output from either the identifying signal generating part 9A connected to one terminal A side or the software servo part 5B connected to other terminal B side.

An identifying signal MS is constituted by a 16-bit shift register 19 as shown in Fig. 7 and an operation part 20 which takes in data of two registers among registers 19 every sample time ΔT, and which outputs its exclusive OR to one end of the register 19. The identifying signal MS, then outputs M sequence signal MS as being 1, 0, 0, 1, 1, 1..., shown in Fig. 8 with amplitude $\pm A$ from its output terminal.

An input/output signal memory part 9B switches control constant setting time switches 11C, 11D from empty terminal B to one terminal A, inputs an input signal MS for the motor 2A and the motor angle θ_m detected by the motor angle sensor 1A, and registers to store it temporary.

A dynamic characteristic model identification part 9C identifies the dynamic characteristic model based on the data stored in the input/output signal memory part 9B.

A control constant calculating part 9D sets the predetermined PID control constant to the software servo part 5B due to the identified dynamic characteristic model.

Further, a non-contact displacement measuring unit

6A is arranged to the robot arm 4, which non-contact displacement measuring unit 6A is connected to a control constant fine adjusting part 10A via the switch 11E. The switch 11E outputs a detection signal X_s to the control constant fine adjusting part 10A when switching one empty terminal A to the other terminal B. The measuring unit 6A here reads displacement X_g of a temporary stop position at the time of a change of direction when the robot arm 4 is caused to perform reciprocating motion.

The control constant fine adjusting part 10A further makes fine adjustment in relation to the control constant, which the control constant calculating part 9D has calculated once as will be described in detail with Fig. 9.

Fig. 9 is a flowchart showing tuning procedure of the tuning device TB1.

As shown in drawing, when a tuning start command is output in STEP 901, each switch 11A, 11B, 11C, 11D, 11E is tilted to one terminal A side in STEP 902.

That is, in Fig. 5, the M sequence signal MS from the identifying signal generating part 9A is input to the motor 2A, and this signal MS and the motor angle θ_m detected by the motor angle sensor 1A are input to the input/output signal memory part 9B.

Accordingly, in STEP 903, when the identifying signal generating part 9A generates the M sequence signal MS1 of relatively large amplitude as shown in Fig. 11, a torque

is generated, which is accompanied with the generation of the M sequence signal MA1, so that the motor 2A results in excitation in STEP 904 as shown in Fig. 10. By the way, in Fig. 11, since it is not possible to illustrate a waveform of the minute M sequence signal MS1, only its amplitude is shown.

STEP 905 illustrates that an input signal MS1 and an output signal θ_m are registered in the input/output signal memory part 9B.

Next, in STEP 906, the frequency response diagram shown in Fig. 12 is identified based on the data stored in the input/output signal memory 9B. The PID control constant is calculated, which produces good time response, and the PID control constant is set to the software servo part 5B.

Next, in STEP 907, respective switches 11A to 11E are tilted toward the terminal B side. In STEP 910, the reciprocating motion is supplied to the robot arm. In STEP 911, a displacement signal of the point of the arm is collected. In STEP 912, a locus displacement signal X_g of the point of the arm at the temporary stop position when turning around is measured, and whether this overshoot amount is in tolerance or not is investigated. The fine adjustment is carried out until the overshoot amount falls within the tolerance at STEPs 913, 908, and 909 when the overshoot amount is over the tolerance.

In these processing, in the dynamic characteristic

model identification part 9C, the stored signal u and data example of V_m (numerical differentiation of θ_m) are performed fitting to the ARMA (Auto Regressive Moving Average) model due to the least-square method indicated in the above described reference documents;

1) "Two-degree-of-freedom PID automatic tuning controller" by Shigemasa, Iino, Kanda, Toshiba Review, Vol. 42, Number 11, pp 822 to 826 (1987)

2) "Signal processing and System identification" by Nakamizo, Takayoshi, Colona Company (1988).

Thus, there is obtained a pulse transfer function of the input/output (4).

$$G_0\left(Z^{-1}\right)=\frac{bZ^{-1}+\cdots+b_nZ^{-n}}{1+a_1Z^{-1}+\cdots+a_nZ^{-n}} \quad \cdots(4)$$

Here, Z^{-1} is a unit of time delay operator, if a sample time of the data is T, and an angular frequency is ω (= $2\pi f$: f is frequency), since there is a relationship of $Z^{-1} = e^{-jWT}$, $G_0(Z^{-1})$ results in the frequency response from the motor input u until the motor angular speed output V_m, which $G_0(j\omega)$ is obtained by substituting $Z^{-1} = e^{-jWT}$ for $G_0(Z^{-1})$. As for the order n, a numerical value is selected where there results in no change in frequency response as increasing the order n from lower one.

Further, in the case of a robot operating against gravity such as a vertical poly-articulated robot, since non-linear gravity component is included in the identifying data, when applying the least-square method as it is, an

error occurs in the identified frequency response. Furthermore, even though a robot is a horizontal poly-articulated robot, non-linear frictional force such as Coulomb frictional force is included. Therefore, a dynamic equation of one-axis arm at low frequency of 0.1 to 1Hz in which these non linear components operate largely is given as follows:

$$m \cdot a_m + d \cdot V_m + F \cdot \mathrm{sgn}(V_m) + g \cdot \sin(\theta_m) = U \cdots (5)$$

Here, θ_m: motor rotation angle,

u: input to the motor,

V_m: 1 time numerical differentiation of θ_m (motor angular speed),

a_m: 2 times numerical differentiation of θ_m (motor angular acceleration),

m: moment of inertia,

$m \cdot a_m$: inertia force term around axis,

d: viscous frictional coefficient,

$d \cdot V_m$: viscous frictional force term around axis,

F: Coulomb frictional force,

$F \cdot \mathrm{sgn}(V_m)$: Coulomb frictional force term around axis,

g: gravity,

$g \cdot \sin(\theta_m)$: gravity term around axis.

When transforming the above equation, there is obtained an equation (6) as follows:

$$[a_m, V_m, \mathrm{sgn}(V_m), \sin(\theta_m)][m, d, F, g]^T = u \cdots (6)$$

Each signal of a_m, V_m, sgn (V_m), sin (θ_m), u of the present equation is the signal obtained in the input/output

memory part 9B, or the signal capable of being calculated therefrom, therefore, it is possible to find unknown m, d, F, g due to application of the least square method. In addition, the following equation is set as:

$$u_2 = u - F \cdot \mathrm{sgn}\ (V_m) - g \cdot \sin\ (\theta_m) \cdots (7)$$

then, a value u_2 is found in such a way that the Coulomb frictional force component and a gravitational component are subtracted from a motor input u, and it is possible to separate the non-linear force when identifying the frequency response with the above described method while using the u_2 and V_m. Further, compensation control of the Coulomb frictional force and gravity is capable of being performed if $F \cdot \mathrm{sgn}\ (V_m)$ and $g \cdot \sin\ (\theta_m)$ are calculated during the software servo control using the obtained F, g, and adds $F \cdot \mathrm{sgn}\ (V_m)$ and $g \cdot \sin\ (\theta_m)$ to the motor input.

In the control constant calculating part 9D, based on the frequency response obtained in such a way as above, first, I-P control constant of a speed loop part 17 in Fig. 6 of the software servo part 5B is calculated (Referring to the reference document 1), a reference document 4) described below).

4) "Control System Design Method based on Model Matching at Cut Off Frequency Band" by Shigemasa, Iino, the 29th Automatic Control United Lecture Meeting Drafts Collection, pp 15 to 18 (1986).

The I-P control constant is calculated so as to satisfy an index (phase margin and gain margin shown in Fig. 17)

of a control system stability specified by the speed loop part 17 based on the above reference documents 1), and 4).

Here, the phase margin represents how many degree of margin until a phase arrives at 180° in the frequency when the gain of an open-loop frequency response of the speed loop becomes 0dB (so called as cut off frequency). The open-loop frequency response is a frequency response from one end to the other end when cutting a loop at the point of control deviation (difference between target value and control amount: immediately front of an integral constant I in the speed loop). Further, the gain margin represents how many decibel of margin until a gain arrives at 0dB in the frequency when the phase of the open-loop frequency response of the speed loop becomes 180°.

By the way, generally, the larger the phase margin, and the gain margin, the more the control system is stable, however, quick-response property toward the target value becomes poor. In the general servo control system, it is appropriate that the phase margin is 50 to 70°, and the gain margin is 12 to 20dB.

On the other hand, in the robot, it is necessary to cope with both the quick-response property and the overshoot (the smaller the better) of the time response. Accordingly, a speed I-P control gain is calculated with a repeat calculation so as to make matching to Bessel Model (gain margin: 15.6dB, phase margin: 67.2°) of reference models performing time response as shown in Fig. 16. Fig.

17 shows the speed I-P loop of open-loop frequency response at this time. In this example, when I is 769, and P is 15.3, the specified gain margin and phase margin are satisfied.

Next, P control constant of a position loop part 14 in Fig. 6 is calculated. Here, the P control constant is calculated, which is made $2\pi/3$ of the cut off frequency of the speed loop shown in Fig. 17 so as to be obtained appropriate time response to a motor angle target value. Since the cut off frequency is 6.8Hz, P is calculated as 14.2. A feed forward control constant FF is introduced so as to enhance the quick-response property within a scope which does not increase the overshoot of the time response, thus the feed forward control constant FF is set to 0.3.

In the software servo part 5D, when a change-over switch is B, the speed loop I-P, and the position loop FF-P are controlled and operated, and the robot arm 4 is controlled upon causing to follow the motor 2A to a rotational angle target value θ_r. By the way, since a motor angular speed target value V_{mr} used for FF turns up in a course where the motor angle target value is created, thus it is not necessary to differentiate the angle target value θ_{mr} over again.

In the control constant fine adjusting part 10A, the displacement signal X_g of the point of arm of the robot which is in control from the non-contact displacement measuring unit 6A is taken in when the change-over switch

is B, and as shown in Fig. 18, the I-P control constant of the speed loop part 14 is performed fine adjustment so that the overshoot of the arm from the target stop position is included in tolerance value ε. A method of fine adjustment is that the gain margin specified at the time of the speed loop I-P control constant calculation is increased gradually, and it is preferable to adopt the I-P control constant at the time the overshoot amount is entered in the tolerance value ε.

By the way, in order to remove a non-tracking component caused by static friction or the like of the robot arm 4, amplitude of the M sequence signal MS1 shown in Fig. 10 should be made large significantly. Further, even though it is made large significantly, whether influence caused by the static friction is removed sufficiently or not is the problem.

Accordingly, in the present example, further as shown in Fig. 14, DC bias DB is supplied to the original M sequence signal MS, as shown in Fig. 13, the robot arm 4 is caused to excite while letting the robot arm 4 slip.

Fig. 15 is a frequency response diagram in the case that the DC bias DB is supplied. It is understood that the frequency response of the low frequency is obtained appropriately compared with the one in Fig. 12.

As described above, according to the tuning device TB1 for the robot control system of the present example, it is possible to set the PID control constant easily, surely,

quickly and in an appropriate time by inputting the M sequence signal MS to the motor 2A.

Further, in the case that a signal MS2 formed in such a way as to supply the DC bias DB to the M sequence signal MS is used, it is possible to supply the control constant with appropriate matching regardless of the low frequency.

Furthermore, since the fine adjusting part 10A is caused to be attached, it is possible to suppress the overshoot amount within the tolerance, thus the robot arm 4 is capable of being positioned with low vibration, and high accuracy.

In the embodiment shown above, there is described an automatic tuning for one axis of the robot, however, it is possible to perform the tuning procedure for each axis of the case of multiple axes in the same method as that described above. That is, in the case of a multi axes robot in which the arms are ranged continuously, if algorithm is built in the robot, which algorithm operates from an axis close to a stand of the robot sequentially, it is possible to prevent from changing tuning result of the axis close to the finger caused by the tuning result of the axis close to the stand.

For instance, in the case that the robot of continuing two arms, first, tuning of one axis is performed. At this time, the second axis is in the state of servo free (without control). Next, tuning of the second axis is performed. At this time, the first axis is made servo lock with already

tuned control constant. With this knack, even though more than three arms are continued, it is possible to perform appropriate tuning.

Fig. 19 shows another constitution example of the software servo part.

That is, the software servo part 5C of the present example, in order to control the objective robot arm 4, there are provided the PID control part 21 of the speed loop in the inside, and the PID control part 22 of the position loop at external side, which the software servo part 5C is constituted with multiple loop such that the inputs/outputs of θ_d, e, $\dot{\theta}_d$, $\dot{e}$, u, $\dot{\theta}$, θ in the drawing are performed. Then, the control constants of the two PID control parts 21 and 22 are set to the appropriate values depending on characteristics of the objective robot arm 4.

First, in the general operation method, the frequency characteristic of the motor 2A relating to an input u and an output $\dot{\theta}$ in Fig. 19 is measured as shown in Fig. 20, and this is approximated upon determining a_0 to b_5, b_0 to b_4 of the transfer function G(S) depending on the following equation as shown in Fig. 21.

$$G(S) = A_2/A_1 \qquad (8)$$

Provided, when A_1 and A_2 are

$$A_1 = a_0+a_1S+a_2S^2+a_3S^3+a_4S^4+a_5S^5$$

$$A_2 = b_0+b_1S+b_2S^2+b_3S^3+b_4S^4,$$

the open-loop frequency characteristic $G_V(j\omega)$ of the speed

loop relating to the input $\dot{e}$ and the output $\dot{\theta}$ in Fig. 19 is that, in

$$G_{V1}(S)=(C_0/S+C_1)G(S)=(C_0/S+C_1)(A_2/A_1) \quad \cdots(9),$$

S is made S=jω. Provided,

ω = 2πf (j is imaginary unit, ω is angular frequency, f is frequency).

The closed-loop frequency characteristic $G_{VC}(j\omega)$ of the speed loop relating to the input $\dot{e}$ and the output $\dot{\theta}$ in Fig. 19 is that, in

$$G_{VC}(S)=G_{V1}(S)/(1+G_{V1}(S))=\frac{(C_0/S+C_1)(A_2/A_1)}{(1+(C_0/S+C_1)(A_2/A_1))}$$

$\cdots(10)$,

S is made S = jω.

The open-loop frequency characteristic $G_{P1}(j\omega)$ of the position loop relating to the input e and the output θ in Fig. 19 is obtained in such a way that S is made S=jω in

$$\begin{aligned} G_{P1}(S) &= (D_0/D+S_1)G_{VC}(S)(1/S) \\ &= (D_0/S+D_1)G_{VC}(S) \\ &= \frac{(D_0/S+D_1)(C_0/S+C_1)(A_2/A_1)}{(1+(C_0/S+C_1)(A_2/A_1))} \quad \cdots(11) \end{aligned}$$

while using the closed-loop frequency characteristic $G_{VC}(j\omega)$ of the speed loop shown in Fig. 22.

The closed-loop frequency characteristic $G_{PC}(j\omega)$ of the position loop relating to the input θ_0 and the output θ in Fig. 19 is obtained in such a way that S is made S =jω in

$$G_{PC}(S)=G_{P1}(S)/(1+G_{P1}(S))=A_4/A_3 \quad \cdots(12).$$

Provided,

$$A_4 = \frac{(D_0/S + D_1)(C_0/S + C_1)(A_2/A_1)}{(1 + (C_0/S + C_1)(A_2/A_1))}$$

$$A_3 = 1 + \frac{(D_0/S + D_1)(C_0/S + C_1)(A_2/A_1)}{(1 + (C_0/S + C_1)(A_2/A_1))}$$

However, in the general operation method, when determining the above described control constant, since characteristics of the robot are applied to the transfer function to represent it with parametric data, and the frequency characteristics of respective loops are found by the algebraic operation using it, in the case of the control system constituted by multiple loop, the more the loop exists in the outside, the higher the order of the algebraic expression is, thus calculation becomes complicated, so that determination of the control constant is difficult, and further, there is a defect that errors are included at the time characteristics of the robot are applied to the algebraic expression.

Accordingly, next, more appropriate operation method concerned with the software servo part 5c of such multiple loop will be described.

As shown in STEP 2301 in Fig. 23, in the present example, operation is started from a taking in work of the characteristic data of the robot.

That is, in STEP 2301, inputs of various frequencies f such as the above described M sequence signal MS are supplied to the robot arm 4 (motor 2A) shown in Fig. 5, then, in STEP 2302, gain characteristic data T_G and phase

characteristic data T_P shown in Fig. 24 are obtained.

Accordingly, the frequency characteristics $G(j\omega)$ of the robot arm 4 relating to the input u and the output $\dot{\theta}$ in Fig. 19, by using the both data T_G and T_P, is represented as

$$G(j\omega) = T_G \bullet \cos T_P + j \bullet T_G \bullet \sin T_P \quad \cdots (13)$$

Therefore, the open-loop frequency characteristic $G_{VI}(j\omega)$ of the speed loop relating to the input $\dot{e}$ and the output $\dot{\theta}$ in Fig. 19 becomes as follows:

$$G_{V1}(j\omega) = ((C_0/j\omega)+C_1)G(j\omega) =$$
$$(C_0/(j \bullet 2\pi f)+C_1)(T_1 \cos T_P + j \bullet T_G \sin T_P) \quad \cdots (14)$$

Thus, when a real part of this equation is taken to as $R_U(G_{V1}(j\omega))$, and an imaginary part is taken to as $I_m(G_{V1}(j\omega))$, gain characteristic data T_{GV1} and phase characteristic data T_{PV1} of the open-loop frequency characteristics of the speed loop can be calculated with

$$\begin{aligned} T_{GV1} &= \sqrt{(R_U(G_{V1}(j\omega)))^2 + (I_m(G_{V1}(j\omega)))^2} \\ T_{PV1} &= -\tan^{-1}(I_m(G_{V1}(j\omega))/R_U(G_{V1}(j\omega))) \end{aligned} \quad \cdots (15)$$

Further, the closed-loop frequency characteristic $G_{VC}(j\omega)$ of the speed loop relating to the input $\dot{e}$ and the output θ in Fig. 19 becomes as follows:

$$G_{VC}(j\omega) = G_{V1}(j\omega)/(1+G_{V1}(j\omega)) = \frac{(C_0/(j2\pi f)+C_1)(T_G \cos T_P + jT_G \sin T_P)}{1+(C_0/(j2\pi f)+C_1)(T_G \cos T_P + jT_G \sin T_P)} \quad \cdots (16)$$

a real part thereof is taken to as $R_e(G_{VC}(j\omega))$, and an imaginary part thereof is taken to as $I_m(G_{VC}(j\omega))$, gain characteristic data T_{GVC} and phase characteristic data T_{PVC}

of the closed-loop frequency characteristics of the speed loop can be calculated with:

$$T_{GVC} = \sqrt{(R_e(G_{VC}(j\omega)))^2 + I_m(G_{VC}(j\omega))^2}$$
$$T_{PVC} = \tan^{-1}(I_m(G_{VC}(j\omega))/R_e(G_{VC}(j\omega))) \quad \cdots (17)$$

Above described calculation processing is performed repeatedly until sufficient control constant is obtained at STEP 2307 while performing a frequency characteristic indication and a time response simulation based on the data obtained due to STEP 2303 to 2306.

Next, in the case that a tuning of the position loop is performed via STEP 2308, processing proceeds to STEP 2309, the same procedure is repeated where the input data is changed to the closed-loop frequency characteristic data of the speed loop.

That is, since the open-loop frequency characteristic $G_{P1}(j\omega)$ of the position loop relating to the input e and the output θ in Fig. 19 becomes as follows:

$$G_{P1}(j\omega) = (D_0+D_1 j\omega) \bullet (G_{VC}(j\omega)/(j\omega)) = (D_0/(j\omega)+D_1)G_{VC}(j\omega) \quad \cdots (18)$$

thus, by using the equation obtaining gain characteristic data T_{GV1} and phase characteristic data T_{PV1} of the open-loop frequency characteristics of the speed loop as it is, it is possible to find the gain characteristic data T_{GP1} and position characteristic data T_{PP1} of the open-loop frequency characteristics of the position loop from the gain characteristic data T_{GVC} and the phase characteristic data T_{PCV} of the closed-loop frequency characteristic of the

speed loop shown in Fig. 21. That is, provided that, $C_0 \rightarrow D_0$, $C_1 \rightarrow D_1$, $T_G \rightarrow T_{GVC}$, $T_P \rightarrow T_{PVC}$, in the equation (14), the open-loop frequency characteristics $G_{P1}(j\omega)$ of the position loop is found. Further, like the equation (15), there are found the gain characteristic data T_{GP1} and the frequency characteristic data T_{PP1}.

Furthermore, also the closed-loop frequency characteristic $G_{PC}(j\omega)$ of the position loop relating to the input θ_0 and the output θ in Fig. 19 can be calculated, provided that, $C_0 \rightarrow D_0$, $C_1 \rightarrow D_1$, $T_G \rightarrow T_{GVC}$, $T_P \rightarrow T_{PVC}$, in the equation (16), with the same equation as the equation (17), there are found the gain characteristic data T_{GPC} and the frequency characteristic data T_{PPC}.

In the present example, even though the control system is one which is constituted with such multiple loops, since it is possible to calculate the whole numerically due to low order of equation while using the gain characteristic data and the phase characteristic data of the inside loop, the calculation is easy and there is a little error.

As mentioned above, in short, in the general operation method, characteristics of the multiple loops are found with a shape of composition g·f(x) of approximate function f(x) (corresponding to equation (8)) and function g(x) representing the frequency characteristics of the respective loops, thus algebraic operation of a high order is forced. To the contrary, in the present example, f(x) is made data-oriented mode, and g·f(x) is calculated

numerically relative to the respective data, thereby operation is performed easily, and there becomes a little error.

The present invention is not limited to the above mentioned embodiments, but the present invention can be executed with the appropriate mode in addition to the above by performing appropriate design change.

[Effect of the Invention]

As above, according to the present invention, since the target value input to the control device body is changed to one concerned with the point of the robot arm, by detecting point operation of the robot arm while providing the external sensor, it is possible to cause the high accurate positioning control to perform while suppressing vibration of the point of the robot arm.

Further, since the external sensor is provided, which detects the overshoot amount at the motion changing point at the time the point of the robot arm is performed reciprocating motion, and the control constant set once is evaluated to adjust, which the control constant is set so that the overshoot amount enters within the predetermined value, it is possible to suppress the overshoot amount within the constant value according to secular change or fluctuation of the load constantly, thus it is possible to perform the positioning control of the robot arm in high accuracy.

Furthermore, in the case that DC bias is applied to

the identifying signal on the occasion of the dynamic characteristic identification, since it is possible to excite the robot arm while sliding the robot arm, the high accuracy control constant is capable of being set while avoiding influence caused by the static friction.

Moreover, in the PID control device in which the position loop and the speed loop are constituted in multiple modes, when setting and evaluating the control constant, in the speed loop, the open-loop frequency characteristic data and the closed-loop frequency characteristic data of the speed loop are obtained while using the frequency characteristic data of single substance of the robot. In the case that the open-loop frequency characteristic data and the closed-loop frequency data of the position loop while using the closed-loop frequency characteristic data of the speed loop in the position loop, it is not necessary to perform high order of the operation using approximate expression, and it is possible to set more appropriate control constant with easy operation and high accuracy.

4. Brief description of the Drawings

Figs. 1 and 2 are block diagrams showing outline of the present invention. Fig. 3 is a block diagram showing a tuning device for a robot control system according to one embodiment of the invention shown in Fig. 1. Fig. 4 is a graph showing its response performance. Fig. 5 is a block diagram showing the tuning device for the robot control system according to one embodiment of the invention

shown in Fig. 2. Fig. 6 is a block diagram showing one example of a detailed software servo part. Fig. 7 is a circuit diagram showing a generating method of M sequence signal. Fig. 8 is a time chart of the M sequence signal generated by a circuit shown in Fig. 7. Fig. 9 is a flowchart of an automatic tuning system. Fig. 10 is a graph showing an output signal due to angular speed. Fig. 11 is a graph showing M sequence input signal due to a torque. Fig. 12 is a frequency response diagram obtained by relationship between Fig. 10 and Fig. 11. Fig. 13 is a graph showing an output signal in the case of applying DC bias to the M sequence signal. Fig. 14 is a graph showing the M sequence signal to which DC bias is applied. Fig. 15 is a frequency response diagram obtained by relationship between Fig. 13 and Fig. 14. Fig. 16 is a response diagram of various reference models. Fig. 17 is a graph showing a phase margin and a gain margin due to the frequency response diagram. Fig. 18 is an explanatory diagram showing tuning system of an overshoot. Fig. 19 is a block diagram showing one example of software servo part constituted by multiple loop Fig. 20 is a graph showing frequency characteristics with respect to the software servo part. Fig. 21 is a frequency characteristic diagram approximating the frequency characteristics. Fig. 22 is a closed-loop frequency characteristic diagram of a speed loop. Fig. 23 is a flowchart showing an operation method of a control constant to the software servo part constituted by the multiple loop.

Figs. 24 and 25 are explanatory diagrams of a gain characteristic data and a phase characteristic data used for an operation of Fig. 23. Fig. 26 is an explanatory diagram of a conventional robot control system. Fig. 27 is a response graph after conventional control constant adjustment.

1 Actuator Sensor

2 Actuator

3 Torque Transmission Mechanism

4 Robot Arm

5 Control Device Body

6 External Sensor

7 Compensation Signal Preparing Unit

8 Target Value Changing Unit

9 Control Constant Setting Unit

10 Control Constant Fine Adjusting Unit

FIG. 1

1 ACTUATOR SENSOR

2 ACTUATOR

3 TORQUE TRANSMISSION MECHANISM

4 ROBOT ARM

5 CONTROL DEVICE BODY

6 EXTERNAL SENSOR

7 COMPENSATION SIGNAL PREPARING UNIT

8 TARGET VALUE CHANGING UNIT

FIG. 2

1 ACTUATOR SENSOR

2 ACTUATOR

4 ROBOT ARM

5 CONTROL DEVICE BODY

6A EXTERNAL SENSOR

9 CONTROL CONSTANT SETTING UNIT

10 CONTROL CONSTANT FINE ADJUSTING UNIT

FIG. 3

1A MOTOR ANGLE SENSOR

2A MOTOR

3A REDUCER

4 ROBOT ARM

5A PID CONTROL DEVICE

6 EXTERNAL SENSOR

7A DYNAMIC CHARACTERISTICS IDENTIFICATION PART

8 TARGET VALUE CHANGING UNIT

9 IDENTIFYING SIGNAL GENERATOR

FIG. 4

ANGLE

TIME T

FIG. 5

2A MOTOR

4 ROBOT ARM

5B SOFTWARE SERVO PART (PID CONTROL CONSTANT)

6A NON-CONTACT DISPLACEMENT MEASURING UNIT

9A IDENTIFYING SIGNAL GENERATING PART

9B INPUT/OUTPUT SIGNAL MEMORY PART

9C DYNAMIC CHARACTERISTIC MODEL IDENTIFICATION PART

9D CONTROL CONSTANT CALCULATING PART

10A CONTROL CONSTANT FINE ADJUSTING PART

FIG. 6

12 FF CONTROL PART

13 P CONTROL PART

14 POSITION LOOP

15 I CONTROL PART

16 P CONTROL PART

17 SPEED LOOP PART

18 NUMERICAL VALUE DIFFERENTIATING PART

FIG. 7

N BIT SHIFT REGISTER

FEEDBACK

FIG. 8

AMPLITUDE

TIME

SAMPLE TIME T

FIG. 9

AUTOMATIC TUNING

901 START COMMAND

902 CHANGE-OVER SWITCH A

903 IDENTIFYING MS SEQUENCE SIGNAL GENERATION

904 MOTOR M SEQUENCE EXCITATION

905 MOTOR INPUT/OUTPUT SIGNAL STORING

906 MOTOR FREQUENCY RESPONSE IDENTIFICATION

907 CHANGE-OVER SWITCH B

908 GAIN MARGIN, PHASE MARGIN SETTING

909 PID CONTROL CONSTANT CALCULATION

910 ROBOT RECIPROCATING MOTION

911 ARM POINT DISPLACEMENT SIGNAL COLLECTING

912 IS OVERSHOOT AMOUNT WITHIN TOLERANCE?

913 INCREASE GAIN MARGIN

END

FIG. 12, FIG. 15

PHASE

GAIN

FIG. 16

RESPONSE

TIME

FIG. 17

PHASE

GAIN

CUT OFF FREQUENCY

PHASE MARGIN

GAIN MARGIN

FIG. 18

OVERSHOOT PERMISSIBLE AMOUNT

TIME

ARM POINT TARGET STOP POSITION

BEFORE FINE ADJUSTMENT AFTER FINE ADJUSTMENT

FIG. 19

SPEED LOOP

POSITION LOOP

FIG. 23

2301 TAKING IN CHARACTERISTIC DATA OF ROBOT

2302 FREQUENCY CHARACTERISTIC DATA PREPARATION

2303 TUNING CONDITION SETTING

2304 CONTROL CONSTANT CALCULATING

2305 OPEN-LOOP, CLOSED LOOP FREQUENCY CHARACTERISTIC DISPLAYING

2306 TIME RESPONSE SIMULATION

2307 SETTING CONSTANT EVALUATION?

2308 IS TUNING OF POSITION LOOP PERFORMED?

2309 CHANGE INPUT DATA TO CLOSED-LOOP FREQUENCY CHARACTERISTIC DATA OF SPEED LOOP

FIG. 26

1 ACTUATOR SENSOR

2 ACTUATOR (MOTOR)

3 (REDUCER)

4 ROBOT ARM

5 CONTROL DEVICE BODY

FIG. 27

ANGLE

TIME T